Wound Field and Hybrid Synchronous Machines for Electric Vehicle Traction with Brushless Capacitive Rotor Field Excitation

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OVERVIEW

Timeline

- Project start date: October 2017
- Project end date: September 2021
- Percent complete: 100%

Budget

- Total project funding: $1,112,707
- U.S. Department of Energy (DOE) share: $999,752

Barriers addressed

- The cost of electric vehicle traction motors has been resistant to reduction
- The rare earth permanent magnet market is subject to significant price and supply volatility
- The power factor's of interior permanent magnet synchronous machines (IPMSMs) and induction machines (IMs) increase the kVA rating and cost of traction inverters

RELEVANCE

- This project developed cost effective wound field synchronous machines (WFSMs) and hybrid excitation machines (HESMs) which meet DOE USDRIVE performance and cost metrics
- Removal of permanent magnets in the rotor through the development of cost effective and robust capacitive power couplers for brushless rotor field excitation power transfer

COLLABORATIONS

- University of Wisconsin-Madison (Prof. Dan Ludois)

FUTURE WORK

- This project has finished though many of the technologies initiated in this project continue to be developed in DE-EE0008869

ACKNOWLEDGEMENTS & CONTACTS

Steven Boyd, U.S. Department of Energy

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APPROACH

Wound Field Synchronous Machines (WFSMs)

- Wound field synchronous machines have several attractive features for use as electric vehicle traction motors
  - No permanent magnets
  - Easy field weakening, reduced iron losses at high speed and high power factor through field excitation control
  - High power factor may allow the inverter kVA rating to be reduced

Brushless Capacitive Power Transfer (CPT)

- Brushless capacitive power transfer uses two sets of rotating capacitors or electrodes in which an AC electric field is established by a high frequency inverter.
- A displacement current can flow through the airgap in the rotating capacitors which is rectified on the rotor using a diode bridge.

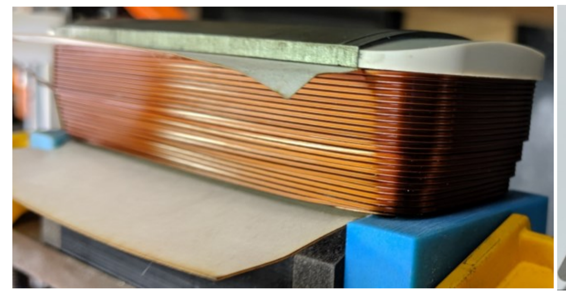
Multiple Generations of WFSMs and CPT Systems

- Three generations of WFSMs and three type of capacitive power coupler (CPC) systems were developed
- Increasing power density WFSMs with each generation
- CPT systems developed include journal bearings, printed circuit board (PCB) based integrated magnetic and capacitive transfer, and large gap PCB in single and three phase variants

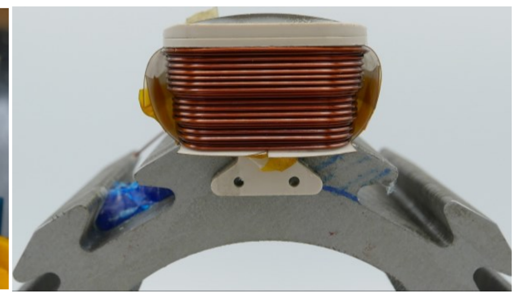
ACCOMPLISHMENTS AND PROGRESS THIS BUDGET PERIOD

Construction of Generation III WFSM

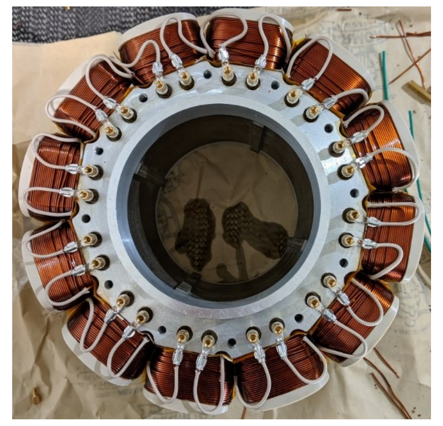
- The efficiency and power density of WFSMs is too a great extent determined by the stator and field slot fills as they are ohmic loss dominated
- Three different high slot fill field windings were designed using square conductors, twisted square conductors, and die compressed round magnet wires
- A hairpin winding stator from a Chevy Volt was used as it is difficult and expensive to prototype a hairpin winding
- The square conductor and twisted square conductor rotors were prototyped



Square conductor rotor pole



Twisted square pole



Square conductor rotor

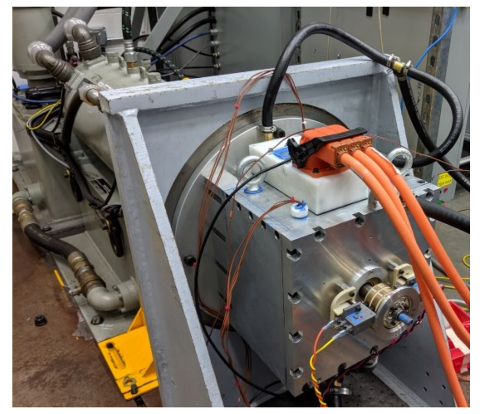
Twisted square rotor

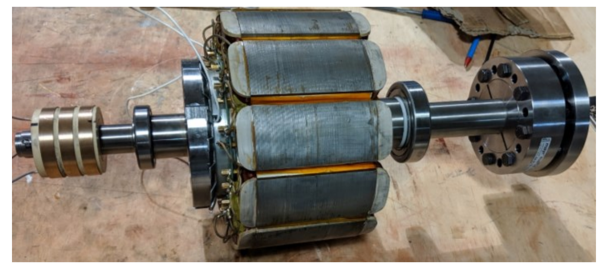
TABLE 1: PREDICTED PERFORMANCE WITH SQUARE CONDUCTOR ROTOR

Load Point	Speed (RPM)	Torque (Nm)	Torque Ripple (%)	J_s (A_{rms}/ mm^2)	J_f (A_{rms}/ mm^2)	Power Factor	Eff (%)
1	4000	131.65	6.83	8.26	7.62	0.97	95.26
2	8000	65.38	5.08	5.80	5.02	1.00	95.59
3	2000	119.68	6.72	7.65	7.10	0.95	93.85
4	4000	454.34	0.55	24.44	15.67	0.98	93.59
5	12000	151.27	6.83	16.60	7.20	0.99	94.66

Dynamometer Testing of Generation III Wound Field Synchronous Machine with Brushes and Slip Rings

- The WFSM with a hairpin stator and square conductor rotor was dynamometer tested at the University of Wisconsin





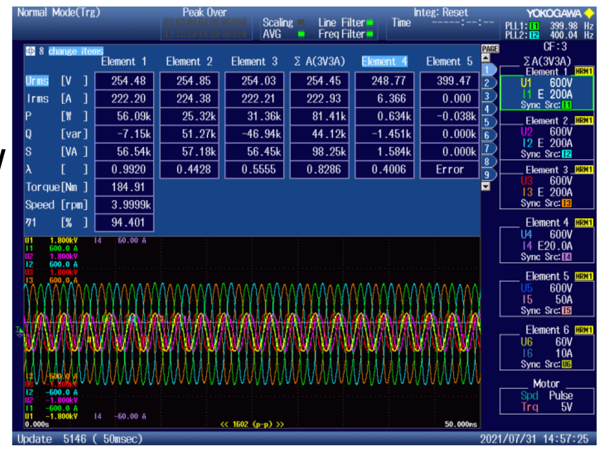
- The ultimate limit to the testing of the power capability of the WFSM prototype is the stator inverter which has a maximum rated current of ~230 A_{rms}. The peak current of the WFSM stator is ~427 A_{rms}
- Only partial load points could be tested for comparison with finite element predictions. The results are very close

TABLE 2: PREDICTED AND MEASURED PERFORMANCE AT LOAD POINT 3 (2000 RPM)

	Torque (Nm)	IPhase (Apeak)	If (Adc)	Power Factor	Eff. (%)
FEA Predicted	119.68	134.55	5.66	0.95	93.85
Experimentally Measured	118.06	137.19	5.92	0.93	93.82

- Results near the current limit of the stator inverter also shown in the screen capture of the power analyzer

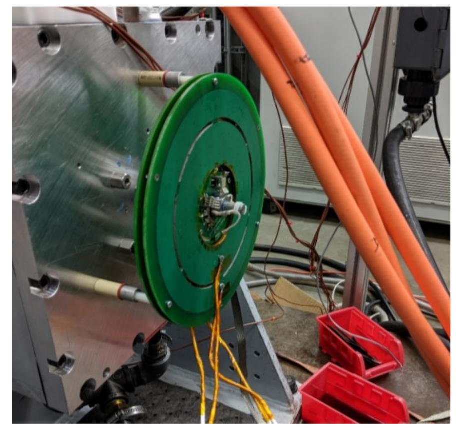
Output power: 77.5 kW
Speed: 4000 RPM
I_s = 22.93 A_{rms}
I_f = 6.366 A_{dc}
Eff = 94.401%



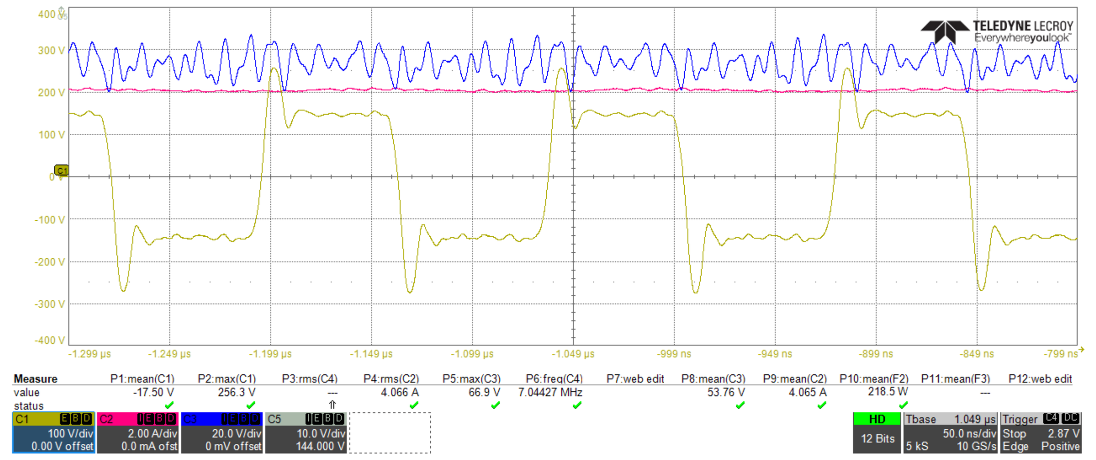
Dynamometer Testing of Generation III Wound Field Synchronous Machine with Single Phase Large Gap PCB Capacitive Power Coupler

- The same WFSM that was tested with brushes and slip rings was also tested with a single phase large gap PCB CPC and two generations of high frequency GaN inverters

Large gap single phase CPC mounted on the WFSM



- The switching frequencies of the GaN inverters were ~1.6 MHz and ~7.1 MHz respectively



Operation of the CPC at ~7.1 MHz and ~4 A field current. The yellow trace is the inverter output voltage and the pink trace is the field current

TABLE 3: PREDICTED PEAK VOLUMETRIC POWER DENSITIES

	4000 RPM Base Speed	6000 RPM Base Speed
Active Material Volume	37.7 kW/l	57.6 kW/l
Volume Including End Turns	24.0 kW/l	36 kW/l

SUMMARY

Approach/Strategy

- This project directly addressed the development of high performance electric traction motors without permanent magnets
- Multiple generations of wound field synchronous machines and capacitive power transfer systems were developed
- This project has demonstrated that WFSMs with brushless capacitive field power transfer can provide a high-power density and low-cost automotive powertrain technology

Overall Technical Accomplishments

- Design and construction of a generation I WFSM rotor with random wound field winding
- Design and construction of a generation II WFSM rotor with die compressed field winding
- Design of two generation III WFSMs: one with die compressed stator and field windings, and one with a hairpin stator and high slot fill field winding
- Construction of the generation III WFSM with hairpin stator and two high slot fill field winding variants: square conductor and twisted square conductor
- Development of a journal bearing capacitive power transfer system
- Development of an integrated magnetic and capacitive power transfer system based on printed circuit boards
- Development of large gap printed circuit board capacitive power transfer system in single and three phase variants
- Development of kilowatt level, megahertz switching frequency, single and three phase high frequency Gallium Nitride inverters for excitation in the capacitive power transfer systems
- Current measurement and phase lock loop control systems for the capacitive power transfer system
- A rotating buck converter with a fixed duty cycle was created for impedance transformation to match the field winding to the high frequency inverter
- A new approach to the design of WFSMs using multi-material, magneto-structural topology optimization
- Parallel flux hybrid excitation machine